NIF Capsule Design Update

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Abstract: We describe several ignition capsule designs, for use in the National Ignition Facility. We will compare these designs for ablator efficiency, ignition margin, implosion and stability performance. This study includes capsule designs driven by x-ray drive profiles with both 300 eV and 250 eV peak temperatures. All of the 300 eV designs are tuned to implode the DT fuel in a nearly identical manner. Capsule designs consist of an ablator material (CH with Br dopant; Be with Cu dopant; and B_4C) encasing a layer of solid DT.   The dopants alter material opacities sufficiently to 1) shield the DT fuel from preheat effects; and 2) develop an ablation front density profile favorable to implosion stability. B_4C has sufficient opacity at 300 eVthat a dopant is not necessary. Issues relating to material properties and fabrication will be described.

Several designs are currently being considered for National Ignition Facility capsules. This paper will only describe indirectly driven capsules, i.e., the laser light is converted to x-rays in a gold (typically) hohlraum. The design work separates into two categories: full scale capsules which absorb 150 to 200 kJ driven by 300eV x-ray radiation obtained from a 1.3MJ laser; and reduced scale capsules which absorb about 100kJ driven by a 250eV peak x-ray profile obtained from a 900kJ laser. The reduced scale effort checks the viability of capsule designs if, for example, drive symmetry issues forced an enlargement of the hohlraum, thus reducing the attainable peak x-ray drive temperature. Full scale designs (300eV, 1.3MJ laser) consist of ablators made of CH doped with Br, Be doped with Cu (distributed in either a uniform or graded fashion), polyimid ($C_{22}H_{10}N_2O_4$), and B_4C. To date, design work on reduced scale capsules (250eV, 900kJ laser) has concentrated on capsules with only one ablator material: Be with graded Cu dopant.

All of the capsule designs considered here utilize four shocks to achieve implosion. These shocks are generated by tailoring the laser pulses hitting the hohlraum to produce an x-ray profile having four distinct steps. A convenient way to visualize these shocks is to plot the logarithmic derivitive of the density at each time point in the simulated implosion (Fig. 1). To produce efficient implosions, each of the shocks should break into the fuel in sequence, producing a distinct velocity jump at the gas-ice interface. Mistiming of these shocks be even a slight amount can result in producing very little or no thermonuclear energy.

In addition to shock timing, achieving high implosion velocity is extremely important to successful capsule performance. A convenient way to measure this is to consider the imploding kinetic energy of the DT fuel. Another way to measure this (especially when considering designs with varying amounts of DT fuel) is to construct a "figure of merit" based on the fact that the

imploding kinetic energy of the fuel must be greater than (or equal to) the energy necessary to ignite the fuel. This figure of merit we define here is simply the ratio of the main fuel kinetic energy to the the energy necessary for ignition. The "energy necessary for ignition" can be crudely estimated by reference to work by Lindl[1] and Levedahl[2] who state:

$$E_{ign} = \frac{1}{2}(0.05)\beta^{\frac{3}{2}}\left(\frac{v}{3}\right)^{-5}$$

where v is the implosion velocity of the DT fuel and β is the ratio of the pressure in the fuel to the Fermi pressure. Unlike final capsule performance indicators like yield, this figure of merit is insensitive to capsule tune and small drive details. Also, it is unambiguous and easy to calculate. We typically quote its peak value to characterize an implosion.

Four capsule designs were selected for study at 300 eV drive. These are shown in Fig. 2. By adjusting the drive for each of the different ablator materials, the DT fuel can be made to implode in a similar fashion. Table 1 lists these capsule designs and several performance characterists: the absorbed energy in kJ, the "figure of merit" defined above, the fuel ρr in g/cm^2, and the yield in MJ. The Be with uniformly doped Cu (designed by Wilson, LANL) is included in the table. Absorbed energies range from 150kJ for CH+Br to 207kJ for Be+uniform Cu. The "figure of merit" which is an indication of implosion velocity, is high for the CH+Br and low for the Be+uniform Cu. Both fuel ρr and yield are similar for all designs. Doping of the ablator material serves two main purposes: 1) it provides x-ray preheat shielding of the DT fuel, allowing the fuel to ultimately achieve maximum pressure and density; 2) it alters the density profile at the ablation front; some combinations will then produce less perturbation growth.

Estimating hydrodynamic stability of perturbations during capsule implosion is crucial to evaluating performance of these different designs. This study only investigates perturbations initially on the outer surface of the ablating shell. Other studies have considered the fuel gas-ice surface and the fuel-ablator surface. A perturbation mode spectrum which derives from a smooth Nova plastic capsule can be approximated by the formula [3]

$$R_{lm} = \varepsilon\left(\frac{6.5nm}{1 + \left(\frac{l\varepsilon}{18}\right)^5} + \frac{5.5nm}{(l\varepsilon + 15)^{1.2}}\right)$$

where R_{lm} is the spherical harmonic amplitude, l is the mode number, and ε=260μm/(radius).

Combining modes 12,24,36,...156 with random phases gives a multimode perturbation amplitude as shown in Fig. 3 with an rms amplitude of 0.031μm. Two-dimensional implosion simulation of five potential NIF capsules using this initial multimode perturbation on the outer ablator surface shows significant stability differences. Figure 4 shows the configuration of the

perturbation at the fuel-ablator interface at the time of maximum interface velocity. That is, the perturbation at this time is the seed for Rayleigh-Taylor perturbation growth as the interface undergoes deceleration from this time forward. The perturbation is significantly larger for the plastic-based capsules than for the Be-based or the B_4C capsules. The CH+Br capsule has 17.1μm perturbation rms, the largest of all, the polyimid has 13.4μm rms; the B_4C has 7.6μm rms; the Be+graded Cu has 6.0μm rms and the Be+uniform Cu has 3.7μm rms

      An explanation of this difference follows. Figure 5 plots density profiles (scaled) and perturbation rms (cm) for the polyimid capsule and the Be+uniformly doped Cu capsule at a time just after the second shock has passed through the fuel-shell interface. The position of the third shock is located at the step in the profile and is identified by the "3". The vertical arrows indicate the position of peak density for the two capsules. For capsule radii greater than the position of peak density, a Rayleigh-Taylor unstable condition exists, since low density material (ablated) is pushing a high density material (remaining shell). For capsule radii smaller than the location of peak density, a Rayleigh-Taylor stable condition exists, since high density material is pushing lower density material. The density profile of the plastic ablator allows the RT unstable condition to be in closer proximity to the fuel-shell interface.

      Figure 6 shows the one capsule designed (so far) to implode and ignite successfully at a peak drive temperature of 250eV. This Be with graded Cu dopant capsule absorbs 115kJ, has a low "figure of merit" (1.08) and a low fuel ρr ($1.28g/cm^2$). One dimensional simulations predict that it produces 5.6MJ energy. This 250eV drive is obtained from a 900kJ laser. Interestingly, a uniformly doped capsule performs almost as well as this graded dopant design. No stability analysis has been done on this capsule to date.

      In summary, several designs appear viable for indirectly driven NIF ignition capsule implosions at 300eV. Each of the ablator materials has specific advantages: CH (Nova experience); polyimid (material strength); Be+Cu (implosion stability); B4C (no doping required). Significant work needs to be done to specify required initial surface finishes for each of these materials. A capsule using a Be ablator with graded Cu doping has been designed to work at 250eV x-ray drive from a 900kJ laser. Stability analysis and integrated modeling needs to be done on this scaled down capsule.

      1) Lindl, J. D. "Development of the indirect drive approach to ICF and the target physics basis for ignition and gain", Physics of Plasmas, Vol. 2, No. 11, Nov. 1995, p3941.

      2) Levedahl, W. K. and Lindl, J. D., "Energy scaling of ICF targets for ignition and high gain", (to be published).

      3) S. W. Haan, "Initial surface perturbation for NIF hydro instability modeling, (internal memo), Aug. 1994.
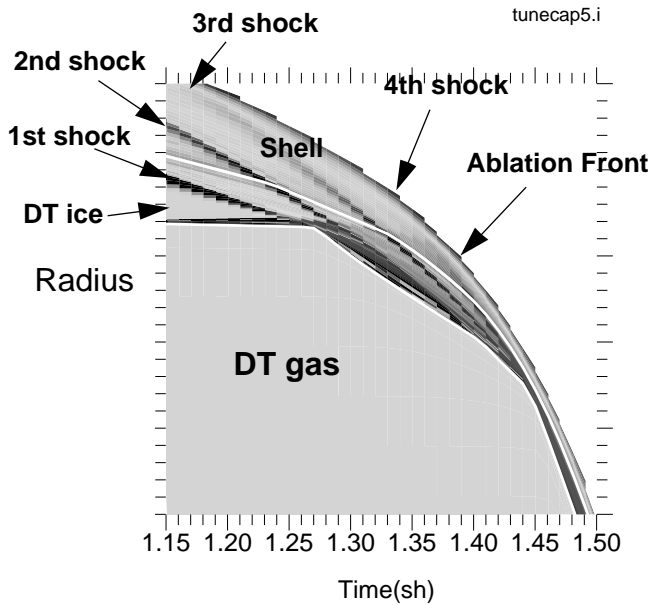
3rd shock

2nd shock

4th shock

1st shock

Shell

Ablation Front

DT ice

Radius

DT gas

1.15 1.20 1.25 1.30 1.35 1.40 1.45 1.50

Time(sh)

Figure 1. Logarithmic derivative of density versus time for the implosion of a typical NIF capsule

$CH+5\%Oxy$ $+0.25\%Br$ — 0.1110

$\rho=1.05$

DT ice — 0.095

DT gas — 0.087

Haan's "PT"

$C_{22}H_{10}N_2O_4$ — 0.1085

$\rho=1.50$

DT ice — 0.095

DT gas — 0.087

Polyimid

Be

Be+
.5%Cu

Be+
1%Cu

Be+2%Cu

— 0.1105

$\rho=2.52$

DT ice — 0.0960

DT gas — 0.0880

Be+graded Cu

B_4C — 0.1070

DT ice — 0.095

DT gas — 0.087

B_4C
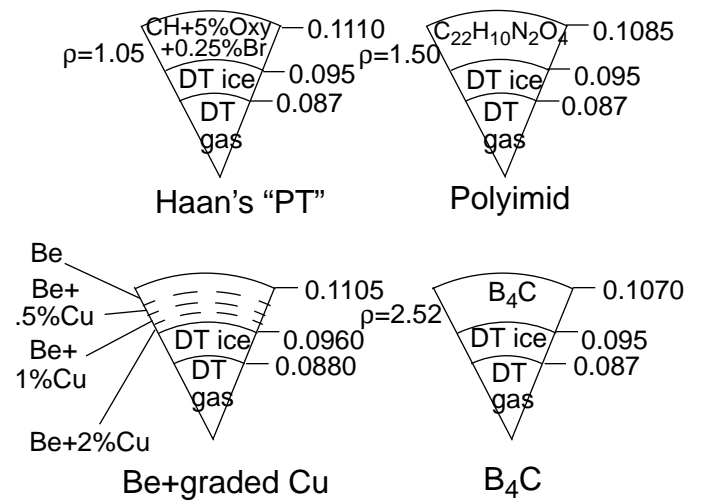
Figure 2. Capsule designs at 300eV peak drive temperature.

6.

E-6

4.

Perturbation
Amplitude
@ timezero
(cm)

2.

0.

-2.

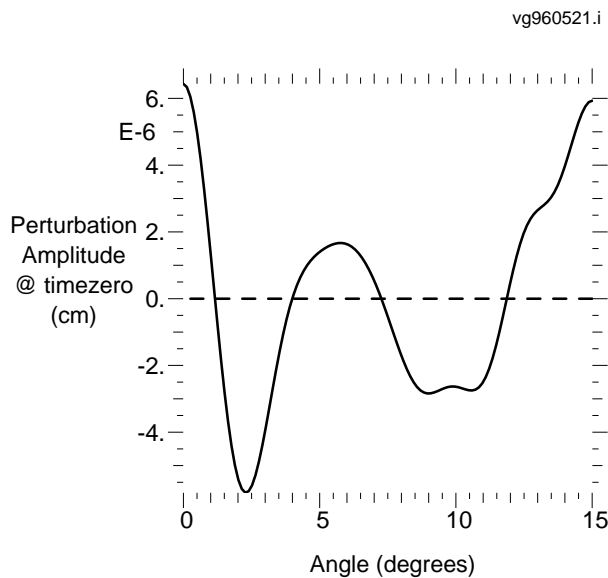-4.

0   5   10   15

Angle (degrees)

Figure 3. Initial multimode perturbation amplitude versus angle applied to the outer surface of each of the implosion simulations. Cosine modes 12,24,36,...156 were combined with random phases to produce this perturbation which has rms of 0.031μm, typical for a smooth surfaced Nova capsule.
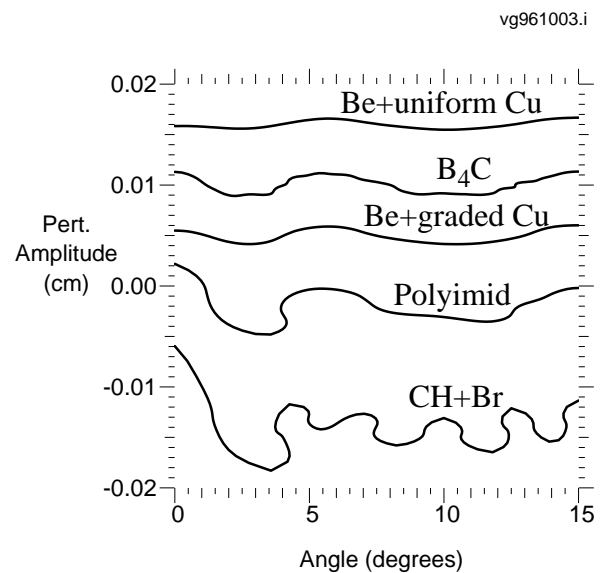
0.02

Be+uniform Cu

B_4C

0.01

Be+graded Cu

Pert.
Amplitude
(cm)

0.00

Polyimid

-0.01

CH+Br

-0.02

0   5   10   15

Angle (degrees)

Figure 4. Perturbation amplitude at fuel-shell interface versus angle at time of maximum interface velocity. CH+.25%Br: rms=17.1μm, polyimid: rms=13.4μm, Be+graded Cu: rms=6.0μm, B_4C: rms=7.6μm, Be+uniform Cu: rms=3.7μm. All perturbations are plotted with same vertical scale but offset for ease of viewing.
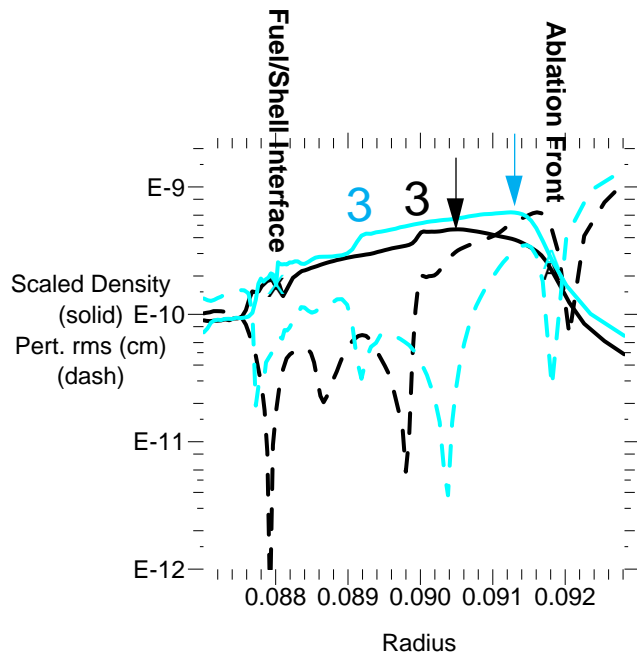
Figure 5. Density (scaled) (solid) and perturbation rms (dashed) versus radius for polyimid ablator capsule (black) and Be+uniform Cu ablator capsule (gray). Position of fuel-shell interface and the ablation front are indicated. The numbers "3" indicate position of the third shock as it proceeds inward. The arrows indicate the position of peak density in each of the density profiles.
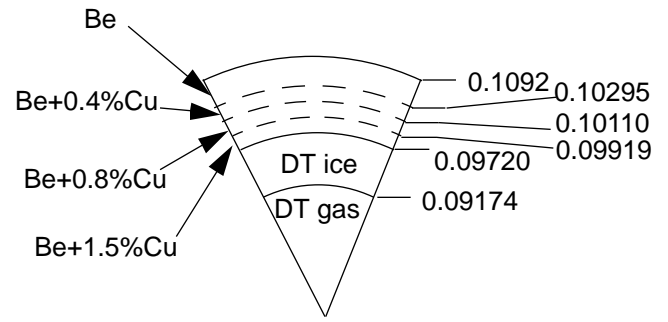

Figure 6. This NIF capsule using a Be ablator doped with graded Cu and driven by a 250eV peak x-ray drive profile from a 900kJ laser can produce 5.6 MJ fusion energy.

Table 1: NIF Capsule Performance

Capsule	Absorbed Energy (kJ)	Figure of Merit	ρr_{fuel} (g/cm^2)	Yield (MJ)
CH+.25%Br	150	4.5	1.67	13.5
Polyimid	158	2.6	1.63	17.5
Be+graded Cu	171	3.5	1.60	15.9
B4C	199	3.5	1.75	18.0
Be+.9%Cu (Wilson)	207	1.5	1.54	19.6